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Injection laser based on composite InAlAs/InAs vertically coupled quantum dots in AlGaAs matrix

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Three-dimensional carrier quantum confinement in the active region has been predicted to lead to remarkable improvements of characteristics of injection laser, i.e., ultralow threshold current density (J_{th}), high characteristic temperature [1], increased gain and differential gain [2]. Significant progress is currently achieved in fabrication and studies of lasers based on quantum dots (QD) formed by the spontaneous transformation of highly strained layer into an array of three-dimensional islands [3]. Low threshold current density at room [4] and cryogenic [5] temperatures, extremely high characteristic temperature [6], and considerably increased material gain [7] have been reported.

However, the areal density of self-organised QDs has been reported to be around $\sim 5 \times 10^{10}$ cm^{-2} [8], it means that only a finite number of charge carries can contribute to lasing. The finite density of states in QD array leads to the saturation of the optical gain at a certain value. This effect is the most strongly pronounced in a laser containing one QD plane in active region where the superlinear increase in J_{th} with output losses is observed [9]. Using vertically coupled QDs considerably reduces the gain saturation [9].

In the present work we report on the further increasing the maximum optical gain in a QD laser by directly increasing the areal density of QDs.
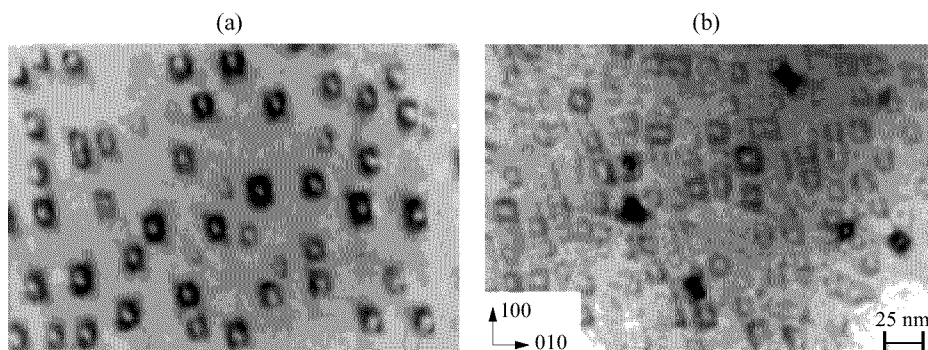
(a)   (b)

Fig 1. Plan-view transmission electron microscopy image of InAs (a) and InAlAs (b) QDs.

Fig. 1 shows the plan-view transmission electron microscopy images of QDs formed by the deposition of InAs (Fig. 1a) and InAlAs (Fig. 1b) layers on AlGaAs surface. The sheet concentration of InAlAs QDs is about 2×10^{11} cm^{-2}, which is much higher
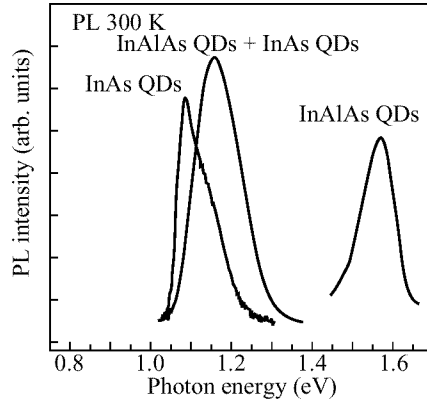
Fig 2. Photoluminescence spectra of structures with QDs in AlGaAs matrix.
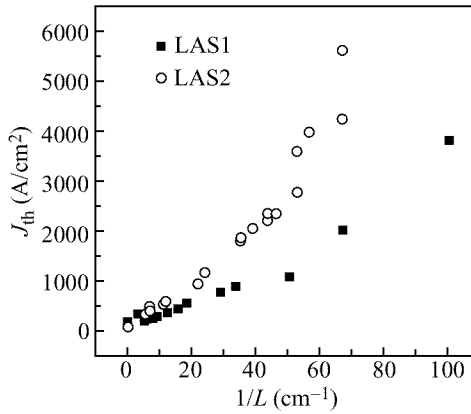

Fig 3. Threshold current density (J_{th}) vs reciprocal cavity length ($1/L$) for LAS1 and LAS2 structures.

than that of InAs QDs possibly owing to the lower migration rate of Al atoms on a growing surface. We assume that using the effect of vertical alignment of QDs [10] we can considerably increase the density of the QD array by depositing first InAlAs QDs followed by In(Ga)As QD planes. Since the bandgap of InAlAs is much larger than that of In(Ga)As, the optical transition energy in the QD array will be determined by In(Ga)As QDs, whereas the density will be set by the InAlAs QDs.

The structures studied were grown by solid-source molecular beam epitaxy (MBE) under the same growth conditions. The first structure contained one plane of InAlAs QDs in $Al_{0.15}Ga_{0.85}As$ matrix, the second contained three planes of InAs QDs separated by 50 Å $Al_{0.15}Ga_{0.85}As$ spacers, and for the last sample, QD array was formed by successive deposition of InAlAs and three InAs QD planes separated by 50 Å $Al_{0.15}Ga_{0.85}As$ spacers. Fig. 2 shows photoluminescence (PL) spectra of the structures described above. Pre-deposition of InAlAs leads to the blue-shift of the PL line as compared to the purely InAs QD sample. This fact is presumably due to the reduction
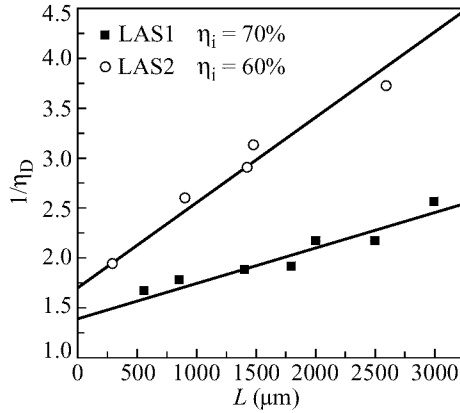
Fig 4. Reciprocal differential efficiency $(1/D)$ vs cavity length (L) for LAS1 and LAS2 structures.
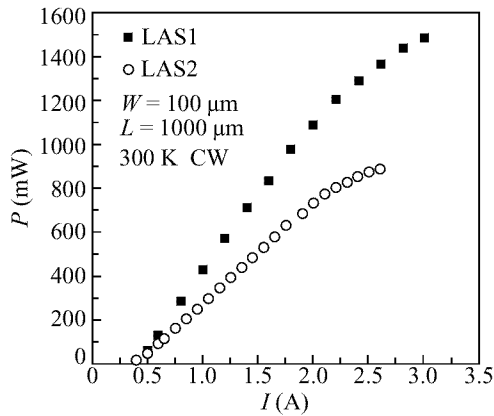

Fig 5. Light output power (P) vs continuous wave drive current (I) for LAS1 and LAS2 structures.

in sizes of QDs. Since the effective thickness of deposited InAs is the same, this should lead to the increase in QD density [11].

Fig. 3 shows Jth as a function of reciprocal cavity length (which is directly proportional to output losses) for the composite InAlAs/InAs QD laser (LAS1) and the similar structure without InAlAs QDs (LAS2) [12]. One can see that the J_{th} of LAS1 is higher than the J_{th} of LAS2 at infinite cavity length (four cleaved facet samples). But when the cavity length is decreased (output losses are increased) the J_{th} of the latter structure increases steeper than in the case of the LAS1. For low losses the lasing is achieved at lower pumping current in laser with lower surface density of QDs and when losses are high the inverse relation is observed. This fact is in agreement with theoretical estimations given in [13].

Using the InAs QDs with higher density also leads to an increase in differential efficiency in the wide range of cavity lengths, internal quantum efficiency, and maximum output power. These effects are demonstrated in Figs. 4 and 5 where the data for LAS1 and LAS2 are given.

In conclusion, we have shown the increase in areal density of InAs self-organized vertically-coupled QDs by depositing InAlAs QD pre-layer. Injection laser with increased QD density demonstrated increased optical gain, differential efficiency and output power.

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